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Combustion process shaping by use of different strategies of multiple fuel injection in a CI model engine

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Abstract Technological advancement in combustion systems of diesel engines triggers the need of fulfilling many contradictory requirements. Among those are such issues as maintenance of environmental standards in terms of the exhaust emissions with a simultaneous preservation of the thermodynamic properties of the combustion process and fuel consumption. The paper discusses the results of research on the influence of the strategies of fuel dose division on the combustion process and operational indexes in a model engine. The paper also contains an exhaust gas analysis conducted with the use of a rapid compression machine. The investigations of the combustion process (development of the self-ignition spots) were conducted using high speed camera. The recorded images related to the period from the onset of the injection to the beginning of the appearance of combustion spots have also been analyzed. The following have been varied: number of doses, size of doses, dwell times and excess air coefficient. The authors performed a comparative analysis of the thermodynamic indexes of the combustion process obtained from the indicator tracings. The achieved results show possibilities of the influencing on the combustion process course and emission of exhaust toxic compounds by application of multiple injection and its properly selected strategy containing proportions in fuel doses and dwell times between them.

Keywords Diesel fuel injection · Fuel dose division · Self-ignition

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Introduction

Technological advancement in combustion systems of diesel engines triggers the need of fulfilling many contradictory requirements. Among those are such issues as maintenance of environmental standards in terms of the exhaust emissions with a simultaneous preservation of the thermodynamic properties of the combustion process and fuel consumption. The fulfillment of the above mentioned requirements requires appropriate strategies of fuel dose division.

Earlier works of the authors were related to the issues of fuel injection [1–3] and research of the combustion of diesel fuel in compression ignition engines [4]. The currently conducted research joins the two issues in the aspect of the influence of diesel fuel dose division on the initial stages of self-ignition. The methods of injection and atomization of diesel fuel are currently an important research problem [5–7].

Literature analysis related to the application of the latest solutions in fuel dose division indicates the following facts:

(a) Literature analysis [8] shows that the division of the injected fuel into two doses has a significant impact on the emission of HC and CO. In a situation when the first dose is greater than the second one an increase in the hydrocarbons and nitric oxides emission was observed at a simultaneous reduction of the emission of particulate matter. An increase in the pilot dose also resulted in an increase in the combustion noise level and the emission of NO_x. These effects were reduced by extending of the injection dwell time. Similar effects were observed in research [9] when a small pilot fuel dose was applied. The investigations presented in [10, 11] also indicate a reduction of the emission of particulate matter;

(b) The results of the investigations presented in [12, 13] indicate an improvement in the fuel combustion and consequently a reduction of the fuel consumption through fuel dose division (as compared to a single fuel dose injection);

(c) From the investigations presented in [9] results the dependence of the NO_x emission from the size of the first fuel dose: a large pilot fuel dose increases the homogeneity of the charge and a reduction of the NO_x emission can be obtained through a delay of the injection of the main fuel dose. In a situation when the injection angle of the first fuel dose was increased by 20°–25° a lower emission of HC and CO was observed;

(d) Literature analysis [8, 13] is related to an engine fitted with an exhaust recirculation system. During the engine operation less oxygen is supplied with the intake air and the fuel dose division results in better mixing of fuel and air inside the cylinder. Owing to the application of fuel dose division a drop in the emission of NO_x and PM was obtained.

(e) The results of the investigations presented in [14] indicate that the application of 25 % of the mass of the injected fuel in the final fuel dose may lead to a reduction of the emission of particulate matter.

Research on combustion process course are very important regarding application of new alternative fuels (e.g., the biodiesel produced by transesterification of soybean oil [15–17]) and rapeseed oil and biomass [18–20] which can be applicated instead conventional ones.

The authors' own research based on the knowledge related to these aspects allowed an assessment of the combustion processes and its thermodynamic indexes in relation to the exhaust emissions. Optical investigations of the combustion processes constituted a supplement to the indicator research and allowed determining of the intensity of formation of the self-ignition spots (hot flames) depending on the applied fuel injection strategy.

Specific objectives

The research related to the fuel dose division and its combustion was conducted with the use of a rapid compression machine (RCM)—Fig. 1. The system parameters were precisely described in [3]. The information contained there indicates the possibility of reflecting of the real engine thermodynamic parameters of the self-ignition process in an RCM. A pneumatic actuation of the piston movement (the pressure of 5 MPa) allowed an obtainment

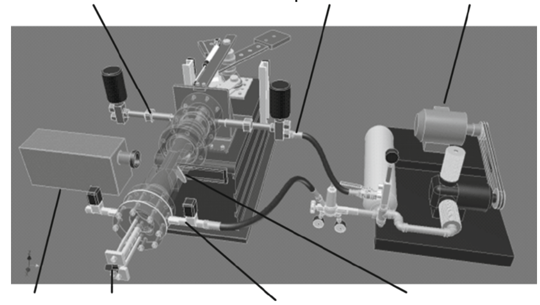


Fig. 1 Rapid compression machine used in the investigations of the development of self-ignition (figure by authors)

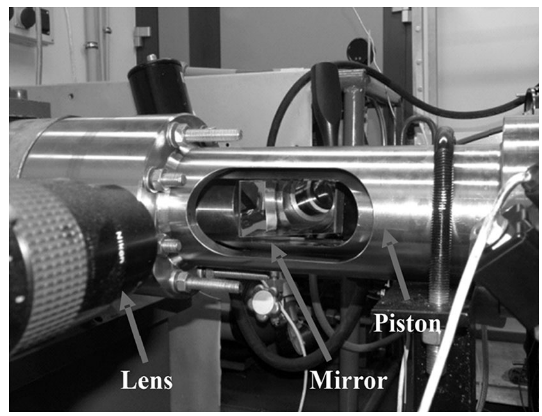
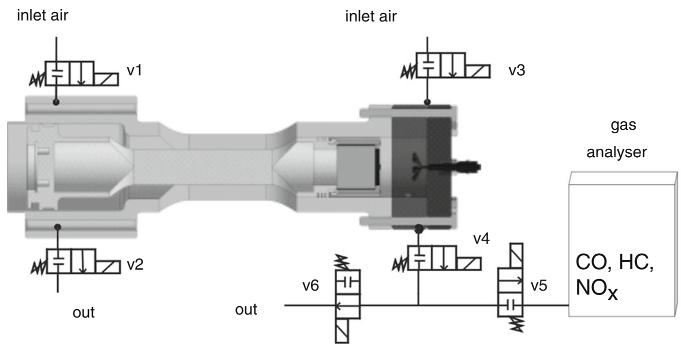


Fig. 2 Optical access to the combustion chamber in the rapid compression machine (figure by authors)

of the compression pressure on the level of 4 MPa. The values of the compression pressure correspond to typical direct injection diesel engine pressures.

The investigations of the combustion process (development of the self-ignition spots) were conducted using High Speed Star 5 camera (by LaVision). The footage was recorded with the filming rate of $f = 5$ kHz, which allowed obtaining images with the time shift of $t = 200$ µs and the resolution of 768 × 768 pixels. The optical access to the combustion chamber was realized from the side of the piston crown through a quartz glass installed in the cylinder guide—Fig. 2.

The investigations of the combustion process were made with an analysis of the concentration of the exhaust components. The analysis is difficult because only a small amount of the exhaust is tested whose mass flow is not continuous (Fig. 3). For this reason the tests were repeated three times presenting an average value from these measurements. The analysis of the spreads indicates 10 % changes during the measurements of the exhaust components



x – valve closed o – valve open	no. of valve					
	1	2	3	4	5	6
inlet	x	x	o	x	x	o
compression	o	o	x	x	x	o
combustion	x	o	x	x	x	o
outlet to gas analyser	x	o	x	o	o	x
outlet w/o gas analyser	x	o	x	o	x	o
purge	x	o	o	o	x	o

Fig. 3 Measurement methodology of concentrations of the exhaust gases compounds in the RCM

Table 1 Plan of the investigations of the injection and combustion in the RCM

Parameter	Value
Optical research	
q_{pilot}/%	0
q_{main}/%	100
t_{inj}/ms	0.3; 0.6; 0.9
P_{inj}/MPa	50; 100
Indicator research	
q_{pilot}/%	0; 25; 50; 75
q_{main}/%	100; 75; 50; 25
q_o/mg @ P_{inj}/MPa	9.4 mg @ 30 MPa
	14.0 mg @ 50 MPa
	23.3 mg @ 80 MPa

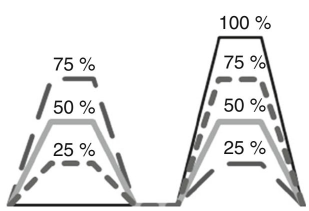


Fig. 4 Fuel dose division strategies in the investigations on the combustion of diesel fuel in the RCM

at the measuring point. In the tests the authors used an exhaust emission analyzer of the accuracy: CO—0.01 %, HC—10 ppm and NO_x—2 ppm.

One of aims was to identify the relation between combustion using one dose and combustion using two doses. Furthermore important is to determinate which dose should be bigger to improve combustion. Therefore were used four strategies. In the investigations the following values were varied (Table 1): the number of doses (1 or 2 fuel doses), the size of the fuel doses (3 settings: in the proportions 0/100; 25/75; 50/50 and 75/25), the dwell times (2 settings: 7 and 14 ms) and the air excess coefficient (3 settings: $\lambda = 1.23$; 2.0 and 3.0)—Fig. 4. Based on the empirical research a comparative evaluation was performed of the thermodynamic indexes obtained from the indicator tracing ($P_{cyl\text{-}max}$, $(dP_{cyl}/dt)_{max}$, of the delay time of cold and hot flames) in connection with the images.

The conditions inside the cylinder during the injection of the individual fuel doses were determined based on the indicator tracing of the pressure inside the cylinder—Fig. 5.

First case: early pilot injection:

- Dwell time: 14 ms
- Piston position during the injection of the pilot dose: 17 mm before TDC
- Temperature inside the cylinder during the injection:
  - (a) Of the pilot fuel dose: 610 K ± 10 K
  - (b) Of the main fuel dose: 775 K ± 10 K

Second case: late pilot injection:

- Injection dwell time: 7 ms
- Piston position during the pilot injection: 7 mm before TDC
- Temperature inside the cylinder during the injection:
  - (a) Of the pilot fuel dose: 700 K ± 10 K
  - (b) Of the main fuel dose: 775 K ± 10 K

The analysis of the injection of diesel fuel required determining of the fundamental quantities related to the fuel injection: the pilot and the main fuel doses (Fig. 6). Similar quantities were determined to describe the combustion process:

(a) For the pilot fuel dose:

- t_{ctrPB}—recorded time of the electric injector opening,
- t_{ctrPE}—recorded time of the electric injector closing,
- $t_{ctrP} = t_{ctrPE} - t_{ctrPB}$—time of the electric injector remaining opened

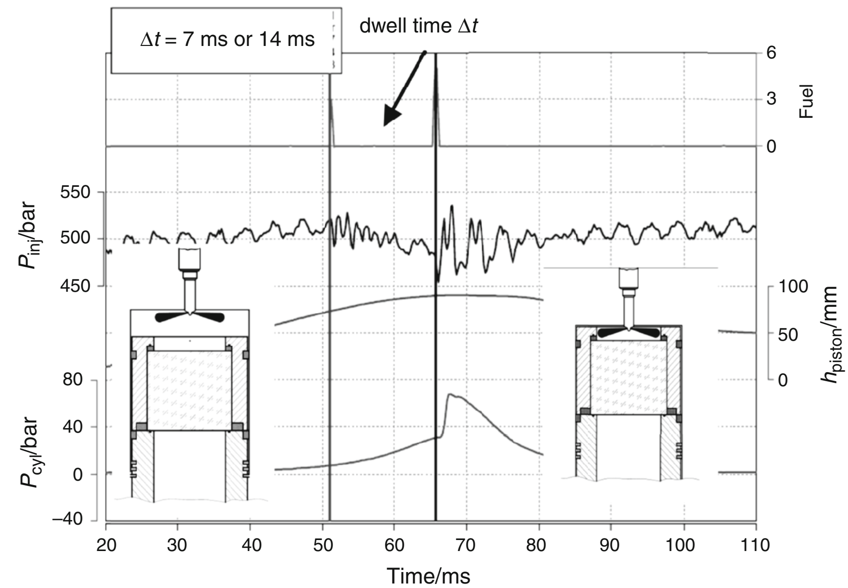


Fig. 5 Geometrical conditions of the piston position during a two-stage injection with varied injection dwell times

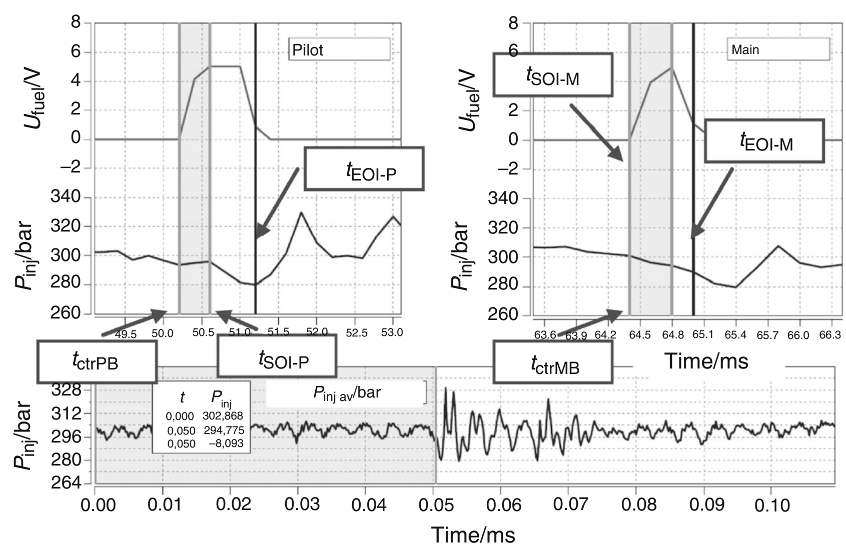


Fig. 6 Determination of the quantities related to the injection of the pilot and the main fuel doses

- $t_{\text{SOI-P}}$—recorded time of the hydraulic injector opening determined based on the pressure of the injected fuel P_{inj} (drop in its value),
- $t_{\text{EOI-P}}$—recorded time of the hydraulic injector closing determined based on the pressure of the injected fuel P_{inj} (increase in its value),
- $t_{\text{HDI-P}} = t_{\text{SOI-P}} - t_{\text{ctrPB}}$—time of the hydraulic delay of the injector opening;

(b) For the main dose:

- t_{ctrMB}—recorded time of the electric injector opening,
- t_{ctrME}— recorded time of the electric injector closing,
- $t_{\text{ctrM}} = t_{\text{ctrME}} - t_{\text{ctrMB}}$—time of the electric injector opening
- $t_{\text{SOI-M}}$—recorded time of the hydraulic injector opening determined based on the pressure of the injected fuel P_{inj} (drop in its value),
- $t_{\text{EOI-M}}$—recorded time of the hydraulic injector closing determined based on the pressure of the injected fuel P_{inj} (increase in its value),
- $t_{\text{HDI-M}} = t_{\text{SOI-M}} - t_{\text{ctrMB}}$—time of the hydraulic delay of the injector opening;

(c) For the combustion:

- t_{SoCFC}—time of thermodynamic onset of cold combustion (i.e., cold flames) determined based

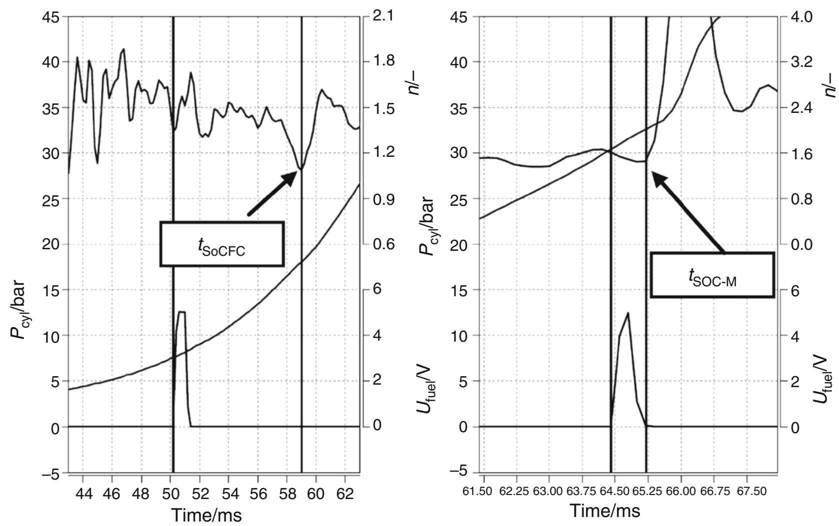


Fig. 7 The conditions for the determination of cold and hot flames for the pilot and main injection respectively

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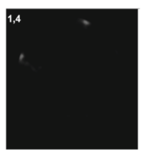
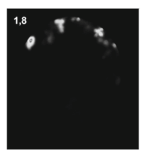
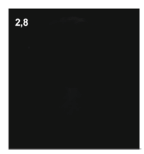
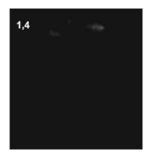
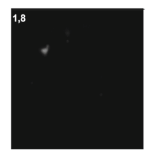
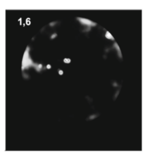
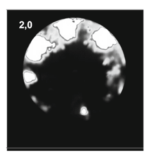
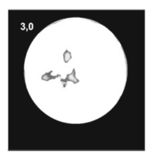
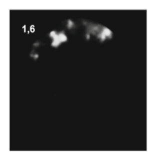
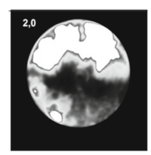
Image 1						
Image 2						
Injection parameters	P_{inj} t_{inj} $t_{SOC\text{-}M}$	50 MPa 0.3 ms 1.4 ms Grains of burning fuel visible	50 MPa 0.3 ms 1.8 ms The flame gradually covers the whole combution chamber	50 MPa 0.3 ms 2.8 ms Very high dynamics of the flame propagation	100 MPa 0.3 ms 1.4 ms The course is similar to 1	100 MPa 0.3 ms 1.8 ms High dynamics of the flame propagation

Fig. 8 The analysis of the self-ignition process of diesel fuel made at different injection pressures and times

on the increase of the polytropic exponent of the compression (determined based on the in-cylinder pressure),

- t_{SOC-M}—time of thermodynamic onset of combustion of the main fuel dose; determined based on the change of the polytropic exponent of compression whose significant growth indicates positive heat release.

The values of the indicated pressure were determined based on the following equation:

$$p_i = \frac{\sum p_{cyl}\Delta V}{V_{End} - V_0} \quad (1)$$

where V_0 is the volume of the cylinder when the piston starts to move and V_{End}—is the cylinder volume when the decompression ends; the time of these changes was identified as 110 ms.

The characteristic points of the graph shown in Fig. 6 indicate the importance of the problem of hydraulic delay of the injector opening during the injection. Such conditions are particularly important when determining the injection dwell times. The extent of the hydraulic delay of the injection of individual fuel doses influences the injection duration and, at the same time, the size of the fuel dose injected in each part of the multiple injection. During the tests, the hydraulic delay of the injection of both the pilot and the main doses was 0.4 ms. This is a value that may correspond to the injection time of a pilot dose of a minimum size. The analysis of the injection times from Fig. 6 indicates that irrespective of the size of the fuel doses a constant value of the hydraulic delay was obtained, which can be deemed as a systematic error. It results from the characteristics of the injector operation and it was independent from the fuel injection pressure and time.

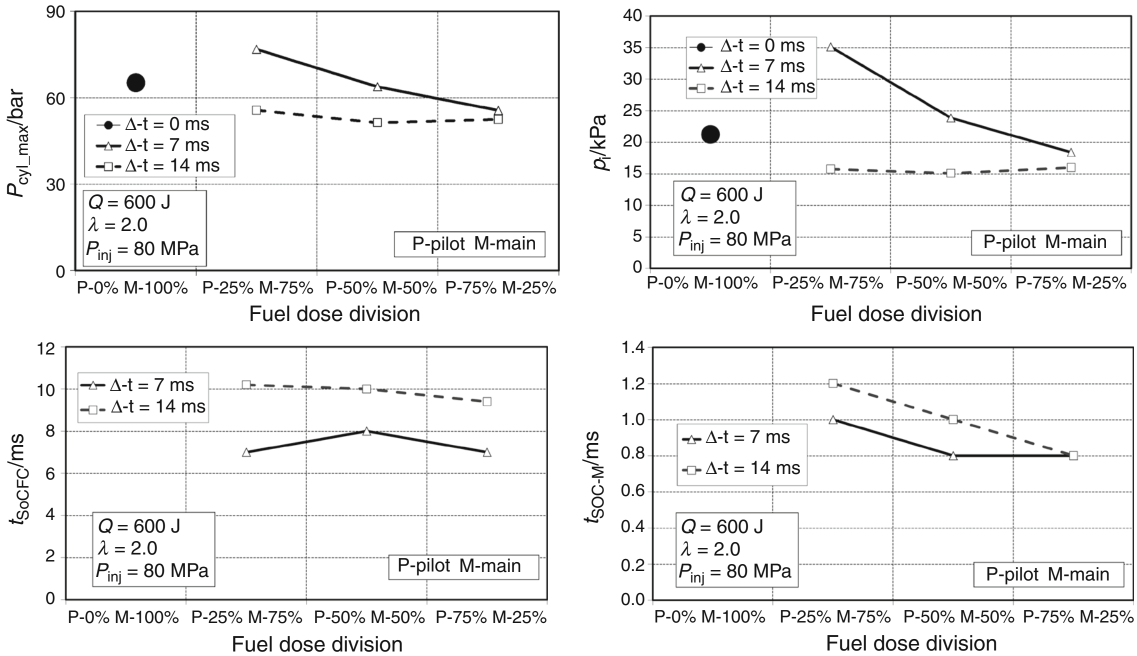


Fig. 9 Combustion indexes during a varied division of the two stage fuel injection

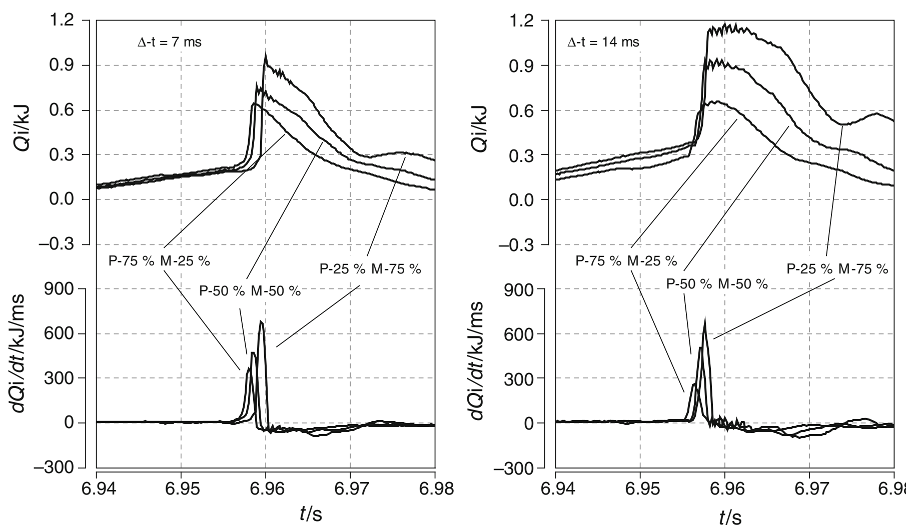


Fig. 10 Heat release and heat release rate during a varied division of the two stage fuel injection ($\lambda = 2$)

The determination of the characteristic points of the process consisted in determining of the onset of the cold combustion (cold flames) of the pilot fuel dose and the onset of the combustion of the main fuel dose (Fig. 7).

From the presented data it results that there is a possibility (based on the polytrophic exponent) of determining of the cold and hot flames based on the indicator research. Yet, based on such research one can only obtain average values of the process, which does not allow their full characteristics. For this reason, for the determination of the onset of hot flames (flame combustion) the authors utilized optical research presented in the next section of the paper.

Results and discussion

The optical analysis of the development of the self-ignition process was conducted for varied injection pressures and for three different injection times (Fig. 8).

The analysis of the images from Fig. 8 indicates an increase in the intensity of the development of early flame processes (hot flames) when a large fuel dose is injected or when the injection pressure is high. The analysis of the images indicates a relation between the size of the fuel dose and the delay time of the self-ignition. Based on the footage the authors observed that the delay of the hot flames of the main injection ($t_{\mathrm{SoC-M}}$) is shorter when small

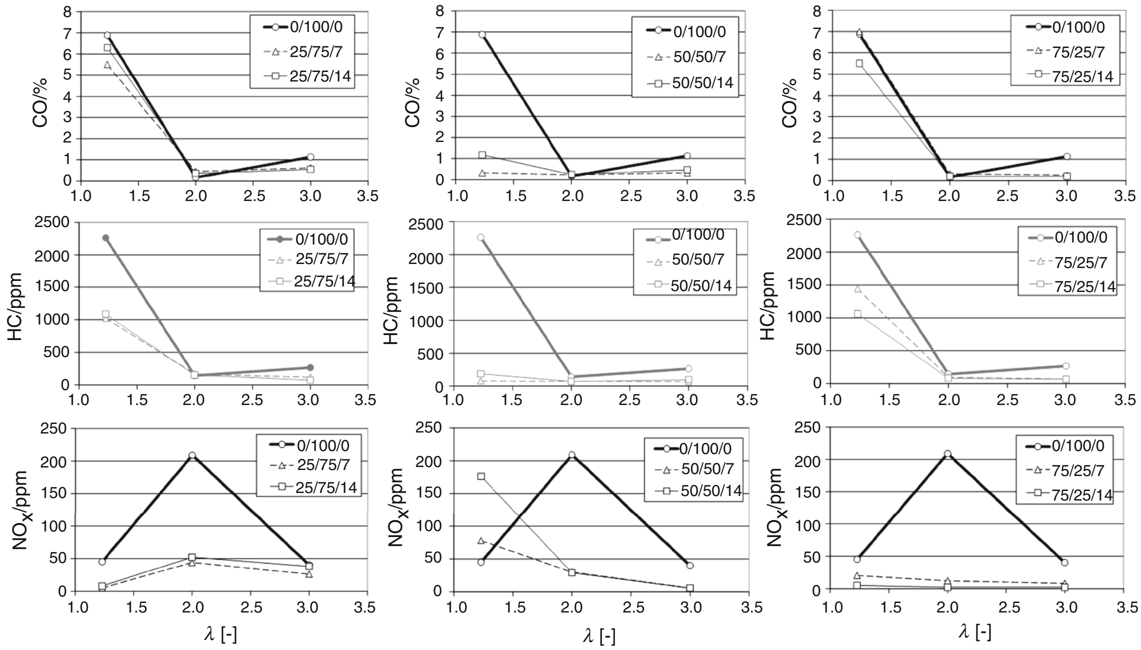


Fig. 11 The concentrations of the exhaust components obtained for varied fuel dose divisions and varied air excess coefficient ($P_{inj} = 80$ MPa; $\lambda = 1.23$; 2.0; 3.0)

fuel doses are injected. This is true for the hot flame delay during both the fuel injection with 50 MPa and the fuel injection with 100 MPa.

The indicator research was carried out according to the research plan contained in Table 1. Additionally, as was presented in Fig. 5 tests were made with two injection dwell times (7 and 14 ms). The research on the multiple injection was compared to the research on the single injection. Indexes of the combustion process were obtained in the form of a maximum cylinder pressure P_{cyl_max}, mean indicated pressure p_i determined according formula (1) and the times of occurrence of cold (t_{SoCFC}) and hot (t_{SOC-M}) flames. These times pertain to the pilot and main injection respectively—Fig. 9.

The analysis of the maximum pressure inside the cylinder indicates a possibility of reaching greater values when multiple injection is applied. Yet, the different dwell times slightly influence the obtained values of P_{cyl_max}. An decrease in the share of the pilot fuel dose leads to the reaching of the highest pressures inside the cylinder. The analysis of the mean indicated pressure, however indicates that the maximum work of the cycle is proportional to the maximum cylinder pressure. The lowest values of this index were obtained with division of fuel dose and longer dwell time.

The time of occurrence of cold flames is determined for the divided fuel dose only as it pertains to the pilot injection. The shortest times, irrespective of the injection dwell times were obtained for even fuel dose division. With a small pilot fuel dose cold flames appear earlier when the dwell times are shorter. This means that the pilot fuel dose is injected to a hotter cylinder charge, which results in a shorter period of the cold flame delay.

The delay time of hot flames was determined for all types of injected fuel doses. An increase in the pilot fuel dose decreases the delay of the hot flames. This results from an sufficient time for a proper evaporation and atomization of the first fuel dose. This may also mean that the second fuel dose reaches the position of the first fuel dose and increases the fuel concentration in certain areas of the combustion chamber. A modification of the size of the pilot fuel dose at its early injection results that the hot flames delay time remains changed (shorter time). This means that during such an injection there is sufficient time from the onset of the pilot fuel dose. The time of occurrence of hot flames is dependent of the size of the main fuel dose (small main fuel dose leads to shorter start of combustion—t_{SOC-M}).

An increase in the pilot fuel dose increases the maximum of heat release and increases maximum heat release rate in the both cases of this fuel dose (shorter and longer dwell time)—Fig. 10. The maximum value of the heat release is bigger in the case of longer dwell time, but the maximum value of heat release rate is the same in the both cases.

The investigations of the combustion and the analysis of the indexes of this process were supported with an analysis of the concentration of the exhaust components during the

RCM operation. There were analyzed the values of the concentrations measured at the fuel injection pressure of 80 MPa and the injection time 1.2 ms divided into portions as shown in Fig. 11. The results were presented for three air excess coefficients: 1.23, 2.0 and 3.0. Figure 11 shows the results ordered in the form of constant fuel dose divisions for two injection dwell times.

An injection of a small pilot dose (25 %) of small dwell times indicates a reduction of the concentration of CO, particularly for low and high excess air coefficients.

Similar trends were observed for hydrocarbons and nitric oxides. The lowest values of the concentrations of the individual exhaust components are observed when the charge combustion is realized with the air excess coefficient of $\lambda = 2$. The concentrations of CO and HC at such an air excess coefficient are independent from the method of fuel dose division and independent from whether the fuel dose is divided or not. A characteristic phenomenon is the occurrence of the maximum concentration of nitric oxides at the air excess coefficient of $\lambda = 2$. This denotes the best course of combustion in terms of the after burning of the carbon monoxide with a simultaneous occurrence of high maximum temperatures of the process. These temperatures facilitate the formation of large amounts of nitric oxides.

The conducted research proves a large potential for the reduction of the exhaust emissions through fuel dose division. The research also indicates much greater benefits if supercharging is applied. This is hinted by the similar values of the CO, HC and NO_x concentrations when the fuel dose is divided and lean mixtures are combusted ($\lambda = 3$).

Conclusions

The presented investigations indicate a possibility of application of fuel dose division in diesel engines.

The conducted research and its analysis allow a formulation of several conclusions:

(a) The usage of the distribution of the dose resulted in an increase of the maximum combustion pressure and the indicated mean effective pressure (IMEP);
(b) The increase of the pilot dose increases the maximum combustion pressure and IMEP;
(c) Cold and hot flames are delayed for any strategy using fuel dose division;
(d) The time of occurrence of cold flames is the shortest when the fuel dose division is even and then it is independent of the injection dwell times;
(e) The time of occurrence of hot flames is determinable based on the analysis of the indicator tracing, yet, better results are achieved when optical analysis is applied; The times are shorter when the injection dwell times are greater;
(f) An increase in the pilot fuel dose increases the maximum of heat release and increases maximum heat release rate in the both cases of this fuel dose (shorter and longer dwell time). The maximum value of the heat release is bigger in the case of longer dwell time, but the maximum value of heat release rate is the same in the both cases.
(g) Fuel dose division contributes to a reduction of the concentration of the exhaust emission components. The most ecologically advantageous air excess coefficient is $\lambda = 2$ at which the influence of the fuel dose division is the least important in terms of the reduction of the exhaust emissions. The best results in the reduction of the emission of nitric oxides are obtained when the fuel dose is divided 25/75 % at low excess air coefficients. An increase in the value of the excess air coefficient results that any fuel dose division is appropriate.

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